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reference output **590**. Harmonic corrector **560** may be switched in and out of the loop by switching its input, output, or both. This form of harmonic correction may also be applied to harmonic locking loops and Costas loops, mixing or phase detector loops, analog or digital (single rate or multi rate).

In this embodiment, as in others, a multiplicity of filters is present. In FIG. **5** for example, low pass filter **530** is followed by loop filter **550** and harmonic corrector **560**. While FIG. **5** shows these three elements separately, other topologies are possible. Rather than implementing these in parallel with their outputs summed as shown, it may be advantageous to place them in series. This is shown in FIG. **6**, showing a harmonic locking phase-locked loop with harmonic correction. This implementation shows harmonic corrector **600** placed in series with loop filter **350**, and feeding VCO **360**.

FIG. **7**. Shows a mixing Costas loop with harmonic correction. Harmonic corrector **700** feeds summer **700**, which combines with the output of mixer **460** to drive loop filter **470** and VCO **480**. In some implementations, it may be desirable to combine these separate filters. This is especially true for digital signal processor (DSP) implementations, where it is common to convolve the separate filters into one equivalent filter section, as is known to the art.

In a second embodiment of the invention, where the harmonic disturbance is well outside the PLL bandwidth, an additional low pass or notch (anti-resonant) filter is added either to the inside of the loop or the outside of the loop. The former is a form of internal correction, and the later is a form of external correction.

In a third embodiment, feedforward cancellation is performed by generating a sinusoid at a phase and frequency so as to cancel out the harmonic disturbance. In this digital approach, an adaptive feedforward canceler, a matching signal is generated, and then used to cancel the residual harmonic error. The matching signal is generated by modeling the residual harmonic disturbance as a Fourier series, and identifying the relevant Fourier coefficients. Cancellation takes these coefficients and injects the matching signal into the loop at an appropriate point to either cancel the signal (external correction), or follow the signal (internal correction). This approach applies to any linear combination of harmonics deemed important. *Feedforward cancellation is taught in Harmonic Generation in Adaptive Feedforward Cancellation Schemes, IEEE Transactions on Automatic Control,* 39(9) pp 1939–1944 by Bodson et al., 1994.

In a fourth embodiment, harmonic cancellation is performed using a repetitive control scheme by using a filtered version of the residual errors on previous rotations of the media. Repetitive control schemes are taught by Tomizuka et al., *Discrete-time domain analysis and synthesis of repetitive controllers, Proceedings of the* 1988 *American Control Conference*, pp 860–866. In this digital approach, N samples of the disturbance are calculated during the rotation of the media. The harmonic portion of the disturbance it repeats with each revolution, and therefore, with each additional N samples. Thus, by calculating and storing N (or a filtered multiple of N) samples of the residual errors, and filtering these samples so as to maintain loop stability, the harmonic disturbance can once again either be canceled or followed by the PLL. This structure provides a periodic integrator with period N. The periodic integrator when coupled into the feedback loop drives out all disturbances of period N.

The foregoing detailed description of the present invention is provided for the purpose of illustration and is not intended to be exhaustive or to limit the invention to the precise embodiments disclosed. Accordingly the scope of the present invention is defined by the appended claims.

What is claimed is:

1. A method of reducing the effects of the harmonic disturbance on a phase-locked loop comprising:

reading a signal from a rotating media;

recovering a reference signal from the rotating media with the phase-locked loop;

applying a harmonic correction to the phase-locked loop, the harmonic correction being generated by notch filtering harmonic content from the reference signal, the harmonic content being induced by rotation of the media.

2. The method of claim **1** where the correction is applied to the phase locked loop continuously.

3. The method of claim **1** where harmonic correction to the phase-locked loop is switched in and out.

4. A method of reducing the effects of the harmonic disturbance on a phase-locked loop comprising:

reading a signal from a rotating media;

recovering a reference signal from the rotating media with the phase-locked loop;

adding a resonant filter to the phase locked loop, the resonant filter increasing the loop gain of the phase-locked loop at a harmonic disturbance, the harmonic disturbance being induced by rotation of the media.

5. A method of reducing the effects of the harmonic disturbance on a phase-locked loop comprising:

reading a signal from a rotating media;

recovering a reference signal from the rotating media with the phase-locked loop;

generating a sinusoid at a same phase and frequency as a harmonic disturbance, the harmonic disturbance being induced by rotation of the media, and

feeding forward the generated sinusoid so as to cancel the harmonic disturbance.

6. A method of reducing the effects of the harmonic disturbance on a phase-locked loop comprising:

reading a signal from a rotating media;

recovering a reference signal from the rotating media with the phase-locked loop;

collecting residual errors from a harmonic disturbance over one or more rotations of the media, the harmonic disturbance being induced by rotation of the media,

filtering the residual errors, and

feeding forward the filtered residual errors.

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HARMONIC CORRECTION IN PHASE-LOCKED LOOPS

CROSS-REFERENCE TO RELATED APPLICATION(S)

This is a divisional of application Ser. No. 09/536,298 filed on Mar. 27, 2000, now U.S. Pat. No. 6,646,964, which is hereby incorporated by reference herein.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to the field of data storage and synchronization. In particular it relates to a method for compensating for a class or repeatable disturbances that are very common in the area of rotating machinery, and specifically in the area of rotating storage media on a spindle. In such cases, spindle rotation causes many disturbances to be injected into the loop used to recover signals used for synchronization. A large fraction of these disturbances are harmonic, that is, they occur at a known frequency which is related to the spindle frequency.

2. Art Background

Disk data storage devices feature rotating media with data recorded on tracks on the media. These tracks may be in the form of a plurality of concentric circles, or they may be in the form of a single spiral. Formatting information is present on the media which allows the disk drive to recover the signals needed to read and possibly write information to and from the media. The media is rotated on a spindle. Imperfections in the spindle apparatus, and in the positioning of the media, introduce disturbances into signals read from the media. Many of these disturbances are harmonic in nature, occurring at a known frequency which is related to the spindle frequency.

For fixed magnetic disk drives, in which the tracks are formatted after the media has been secured to the spindle, the dominant harmonics are most closely related to minor defects and tolerances in the spindle itself. However, in removable media, such as an optical storage medium, including but not limited to DVD+RW, the dominant feature is the imprecise positioning of the media and therefore the tracks relative to the true center of the spindle. This positioning offset causes eccentricity in the path which the tracks will take. This means the tracks will not pursue a true circle around the axis of rotation of the spindle; instead, the tracks will have an eccentricity which manifests itself as a set of sinusoidal deviations from the true circular path.

In a storage device using a rotating storage medium, the act of reading or writing data necessitates the generation of a clock signal to keep the data synchronized. Furthermore, this clock must be synchronized to the rotating medium itself, so that the data can be repeatably positioned on, and recovered from, the storage medium. In order to generate a clock for reading or writing, it is common to use a phase-locked loop (PLL) which generates a repeatable clock which uses as its input a reference signal measured from the rotating medium. Phase-locked loops have the general nature that they are feedback loops applied to electronic signals rather than motion control signals.

A multiplicity of loops are commonly used in rotating storage devices. One loop maintains the tracking position of the read/write assembly. Another loop produces the reference clock used for reading and writing data. A third possible loop is used in far field devices, such as rewriteable optical storage, to maintain the height of the readback mechanism or the focus position of the objective lens. Both of the former loops exhibit sensitivity to track eccentricity. The sensitivity of the tracking position loop to the harmonic disturbances described above can be reduced using a variety of methods known to the art. However, even if the distorted track were being followed perfectly, the mere act of following the eccentricity would produce differences in the reference clock period around the circumference of the track.

What is needed is a method for correcting clock recovery loops in the presence of harmonic disturbances.

SUMMARY OF THE INVENTION

Disturbances introduced into a phase-locked loop (PLL) by harmonic sources in rotating storage media are reduced by applying harmonic correction. Harmonic correction may be present at all times in the PLL, or may be switched in once loop lock has been obtained. Harmonic correction reduces the resultant noise and jitter of the loop. The nature of the harmonic correction employed depends on the nature of the disturbance, as well as the nature of the loop. In a first embodiment, where the disturbance is well within the PLL bandwidth, an additional integrating pole or a bump (or resonant) filter is added to the loop. In a second embodiment, where the disturbance is well outside the PLL bandwidth, an additional low pass or notch (anti-resonant) filter is added to the loop. In a third embodiment, harmonic correction is obtained by generating a sinusoid or a combination of sinusoids at a phase and frequency so as to cancel out the disturbance; this signal is added as a feedforward signal. In a forth embodiment, harmonic correction is obtained in a repetitive control scheme using a filtered version of the residual errors on previous rotations of the media as a feedforward signal to cancel harmonic effects. These embodiments may be repeated for each harmonic frequency at which a significant disturbance is present, and may be used in combination with each other.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention is described with respect to particular exemplary embodiments thereof and reference is made to the drawings in which:

FIG. 1 shows the effects of track eccentricity in a disk drive,

FIG. 2 shows an optical disk drive system with a phase-locked loop,

FIG. 3 shows a harmonic locking phase-locked loop using a phase detector,

FIG. 4 shows a mixing Costas loop,

FIG. 5 shows a mixing loop with harmonic correction,

FIG. 6 shows a harmonic locking phase-locked loop with harmonic correction,

FIG. 7 shows a mixing Costas loop with harmonic correction,

DETAILED DESCRIPTION

In removable media storage devices, imprecise positioning of the disk on the rotating spindle introduces errors. As shown in FIG. 1(*a*), disk media **100** has a circular track **110** and disk center **120**. The center of disk **100**, of track **110**, and disk center **120**, are all coincident. Unfortunately, when the media is clamped in place on the spindle of a disk drive, the center of the spindle may not be coincident with the center of the disk; the two centers may be offset. Each time the media is removed and replaced, this misalignment may